TIGHT FOCUSING METHOD AND SYSTEM

FIELD OF THE INVENTION

This invention is generally in the field auto-focusing techniques, and relates to a method and device for tight focusing a beam of electromagnetic radiation while recording/reading information in a three-dimensional storage medium.

BACKGROUND OF THE INVENTION

Three-dimensional optical memory devices have been developed being aimed at significantly increasing the amount of recordable data, as compared to the conventional two-dimensional devices (typically two data-layer containing structures).

U.S. Patent No. 5,268,862 discloses a three-dimensional optical memory, in which an active medium, typically a photochromic material and more typically spirbenzopyran, is maintained in a three-dimensional matrix, typically of polymer, and is illuminated in selected regions by two light beams, of 532nm and 1064 nm wavelength, to change from a first, spiropyran, to a second, merocyanine, stable molecular isomeric form by process of two-photon absorption. Regions not temporally and spatially coincidently illuminated are unchanged. Later illumination of the selected regions by two light beams, of 1064nm wavelength each, causes only the second, merocyanine, isomeric form to fluoresce. This fluorescence is detectable by photodetectors as stored binary data. The three-dimensional memory may be erased by heat, or by infrared radiation, of 2.12 microns wavelength. Use of other medium permit the three-dimensional patterning of three-dimensional forms, such as polystyrene polymer solids patterned from liquid styrene monomer. Three-dimensional displays, or other inhomogeneity patterns, can also be created.

U.S. Patent No. 6,071,671 discloses a method of manufacturing a fluorescent 3-D optical memory device implementing an active medium capable of storing information at high information density, and an optical memory device manufactured by this method. The active medium employed in the present invention is a material capable of existing in at least 2 isomeric forms. Transition from one form to another can be induced upon illuminating this material by a "writing" electromagnetic radiation having a first spectrum. At the same time the other isomeric form is capable of fluorescence upon illuminating this material by a "reading" electromagnetic radiation with a second spectrum. By virtue of illuminating with a radiation having the first spectrum there are created elemental cells within a medium material, containing substantially the same isomeric form thereof, which can be either that form which is capable of fluorescence or the other one which is not. The information is stored within the medium as numerical values associated with the amount of one of the isomeric forms of active medium contained within elemental cells distributed within the active medium.

WO 01/73779, assigned to the assignee of the present application, discloses a three-dimensional memory apparatus for storing information in a volume comprising of an active medium. The active medium is capable of changing from a first to a second isomeric form as a response to radiation of a light beam having energy substantially equal to first threshold energy. The concentration ratio between a first and a second isomeric form in any given volume portion represents a data unit. The active medium in the memory apparatus includes diarylalkene derivatives, triene derivatives, polyene derivatives or a mixture thereof. Reading the data units from the isomeric states of the active medium is based on the fact that the two isomeric forms have substantially different absorption coefficients for absorbing energy of second threshold energy. Reading may also be carried out by measuring the scattering pattern of the two isomeric forms.

Optical storage devices have customarily been dependent on the ability to focus a laser beam to a tight spot of the order of its diffraction limit so as to allow

for squeezing of as much information as possible onto the surface of the storage device. This requires correction for optical aberrations.

U.S. Patent No. 5,841,753 discloses an optical information storage system having a multi-recording-layer record carrier and a scanner device for the carrier. The scanner produces a radiation beam which is compensated for spherical aberration for a single height of the scanning spot with the stack of layers. The height of the stack is determined by the maximum spherical aberration permissible for the system. The number of layers in the stack is determined by the minimum distance between layers, which depends on the crosstalk in the error signals due to currently unscanned layers.

U.S. Patent No. 6,064,529 describes a method of spherical aberration correction using flying lens in an optical access device for a moving optical data storage media. This technique utilizes a single incident light beam and detection of reflections of this beam from the media. The flying lens is located near an outer surface of the media, and an objective lens is spaced from the flying lens. The flying lens and objective lens co-operate to substantially offset a variable range of negative spherical aberration occurring in the media by forming a positive spherical aberration which substantially cancels the negative spherical aberration.

U.S. Patent No. 6,091,549 discloses a method and apparatus for adjustable spherical aberration correction and focusing. According to this technique, two lenses separated by an air gap are used to provide spherical aberration compensation and focusing of a light beam to a focal point inside a data storage medium. The thickness of the air gap determines the amount of spherical aberration compensation provided. The distance between the lens pair and storage medium determines the depth of the focal point within the storage medium. The internal surfaces of the lenses which define the air gap are preferably planar. The external surfaces of the lenses are aspheric to provide accurate focusing and positive spherical aberration. The air gap between the lenses may also be formed by curved internal surfaces, in which case it is best for the focus lens to have a concave

internal surface. The apparatus and method of the present invention reduces the number of optical components required for an optical data reading/writing device.

U.S. Patent No. 6,310,840 discloses an optical scanning device for use in an optical player. The scanning device includes an optical lens system for focusing a light beam into a scanning spot on a track of an information carrier. The scanning device includes a first actuator for displacing the lens system parallel to an optical axis for focusing the light beam on the information carrier. The lens system includes a main lens or objective lens and an auxiliary or solid immersion lens, providing the lens system with a large numerical aperture, so that the scanning device is suitable for scanning information carriers with a high information density, such as, for example, high-density compact discs. The auxiliary lens is secured in a fixed position to the housing of the lens system, while the main lens is suspended in the housing in a direction parallel to the optical axis by an elastically deformable mounting unit. The lens system includes a second actuator for moving the main lens relative to the auxiliary lens in a direction parallel to the optical axis for compensating for spherical aberration in a transparent protection layer of the information carrier. Thus, the necessary power of the first actuator is limited considerably.

SUMMARY OF THE INVENTION

There is a need in the art to facilitate reading and recording information processes while correcting for chromatic and spherical aberrations in a data storage medium of the kind where a radiation response of the medium is excitable by exciting reading and recording beams of different wavelengths and the excited response is of a wavelength different from that of the reading and recording beams. The data recording process is typically concurrent with the reading process from the same sites in the medium. In the medium of this kind, the reading and recording beams of different wavelengths are thus to be simultaneously focused to and the response of a third different wavelength is to be collected from the same site.

It should be understood that the term ***"recording"*** used herein signifies one of the data writing and erasing processes.

The present invention provides for focusing two exciting beams of electromagnetic radiation of different wavelengths (e.g., laser beam) onto the same site in a three-dimensional medium at various depths while keeping the desired beam spatial characteristics, thereby enabling reading and recording data in the medium. The main idea of the present invention consists of compensating for the chromatic and spherical aberrations over the whole range of focal depths that are of interest to a particular implementation.

As indicated above, in order to enable focusing a laser beam to a tight spot of the order of its diffraction limit and thereby allow for squeezing as much information as possible onto the surface of the storage device, all optical aberrations are to be corrected. The spherical aberration of a particular optical setup is dependent on the nature of the material the light traverses and the length of the path through it. When dealing with simultaneous focusing of two light beams of different wavelengths via the same focusing/collecting arrangement, a problem with chromatic aberrations of focusing arises.

The present invention takes an advantage of the facts that optical storage devices have customarily stored data within a particular and known depth of transparent material, and the material can be excited to respond to specific known wavelengths of exciting radiation, and provides for a method and optical system that corrects for chromatic and spherical aberrations appropriate to the particular depth standard for a particular data storage medium.

While reading/recording data in a three-dimensional storage medium (e.g., a monolithic translucent material), incident light beams of different wavelengths after passing through a lens arrangement traverse two distinct materials (e.g., air followed by a clear plastic) and is focused within the second material (storage medium). The present invention solves the problem of correction of chromatic and spherical aberrations by tailoring the focusing/collecting arrangement to enable focusing of two exciting light beams of different wavelengths onto desirably

distanced from each other sites in the medium and detecting excited light coming from the medium while correcting for chromatic and spherical aberrations of focusing/collection. This is implemented by appropriately designing the focusing/collecting arrangement (i.e., a number of lenses, their relative accommodation and geometry) to adjust a degree of divergence/convergence of the exciting light beams' when arriving to the focusing/collecting arrangement, as well as the collection of the excited light, and the light propagation in between the focusing/collecting arrangement and the medium. It should be noted that with regard to excited light, the focusing/collection assembly receives a portion of this light impinging onto the focusing/collecting arrangement and forms an excited light beam to propagate towards a detector assembly. Thus, the term ***"excited light beam"*** or ***"excited beam"*** used herein signifies either one of excited radiation or shaped excited beam, depending on the excited light propagation location, namely, respectively, between the focusing/collecting arrangement and the medium, and between the focusing/collecting arrangement and the detector assembly.

Thus, according to one broad aspect of the present invention, there is provided a method for use in recording/reading data from an array of data units within a three-dimensional storage medium, the method comprising:

(i) providing exciting radiation in the form of first and second light beams of first and second different wavelengths, respectively;

(ii) concurrently directing said first and second light beams and focusing them onto desirably distanced from each other sites in the medium and collecting excited light of a third wavelength coming from the medium to form a third excited light beam and direct it towards a detector assembly, while correcting for chromatic and spherical aberrations of the light focusing and collection;

(iii) sequentially repeating step (ii) for successive sites in the medium with varying depth of focus.

The focusing and collecting include passing the exciting light beams and the excited light through the same focusing/collecting arrangement. The geometry of

the focusing/collecting arrangement and its accommodation relative to the medium and to light source and detector assemblies are optimized to be capable of focusing each of the exciting light beams to said desirably distanced from each other sites in the medium and detecting the beam of the collected excited light coming from the excited site in the medium.

The focusing/collecting arrangement comprises two lens assemblies accommodated in an optical path of the exciting and excited light beams and being arranged in a spaced-apart relationship along an optical axis of the focusing/collecting arrangement. One of these two lens assemblies is designed to perform the majority of light bending required for the focusing of the exciting light and collecting the excited light, and the other lens assembly is designed to compensate for changing spherical aberration introduced by a change in a thickness of the medium into which the exciting light is being focused. The lenses of the focusing/collecting arrangement have different surface geometries, at least one of these surfaces being aspheric.

Preferably, that one of the two lens assemblies which is designed to compensate for changing spherical aberration is located closer to the medium. This lens may be a flying lens.

That one of the two lens assemblies which is designed to perform the majority of light bending may be configured to define two lens portions of different materials and geometries. In this case, the lens portions may be separate lens elements arranged in a spaced-apart relationship along the optical axis either with a gap between them or being attached to each other.

Alternatively, that one of the two lens assemblies which is designed to perform the majority of light bending may be located closer to the medium. In this case, the other one of the two lens assemblies may be a multiple-lens assembly, for example including three spaced-apart different lenses.

The variation of the depth of focus is preferably implemented by displacing at least one of the lenses of the focusing/collecting arrangement with respect to at least one other lens thereof along the optical axis, and more preferably displacing

only that one of the lens assemblies which is designed to perform the majority of light bending. Generally, however, the entire focusing/collecting arrangement, as well the light source and detector assembly can be movable with respect to each other and/or with respect to the medium.

The correction of chromatic aberrations of focusing/collection may be carried out during the exciting beams' propagation towards the focusing/collecting arrangement and the excited beam propagation from the focusing/collecting arrangement, by pre-shaping the exciting beams and post-shaping of the collected excited beam, while correction of spherical aberration is carried out by the focusing/collecting arrangement. The pre-shaping consists in providing a desired degree of the beam divergence or convergence when arriving at the focusing/collecting arrangement Several examples of pre-shaping are possible: The pre-shaping may consist in providing a slight divergence or convergence of each of the exciting beams, thereby providing semi-infinite conjugation of the exciting beams. The pre-shaping may consist in providing a larger degree of divergence or convergence of each of the exciting beams, so as to provide finite conjugation of the exciting light beams. The pre-shaping may consist in collimating one of the first and second exciting light beams and providing a slight divergence/convergence of the other exciting beam when arriving to the focusing/collecting arrangement so as to provide the semi-infinite conjugation of said other beam. The pre-shaping may include collimation of each of said first and second exciting light beams. The post-shaping of the excited light beam consists of providing a desired divergence or convergence of the excited beam when arriving at the detector assembly.

The first and second exciting beams may be, respectively, reading and recording light beams, or both be reading or recording light beams.

According to another broad aspect of the invention, there is provided an optical system for use in recording/reading data from an array of data units within a three-dimensional storage medium, the system comprising:

(a) a light source assembly operable to produce exciting radiation in the form of first and second light beams of first and second different wavelengths,

respectively, thereby enabling excitation of desirably distant from each other sites in the medium to produce excited light of a third wavelength;

(b) a detector assembly for receiving the excited light and generating data indicative thereof;

(c) a focusing/collecting assembly accommodated in the optical path of propagation of said exciting and excited light, a geometry of said focusing/collecting arrangement and its accommodation relative to the medium and to the light source and detector assemblies being optimized to enable directing the exciting light beams and focusing them onto said desirably distant from each other sites and enable collecting of the excited light to form an ex cited light beam to be directed to the detector assembly, while correcting for chromatic and spherical aberrations of focusing; and

(d) a drive means associated at least with the focusing/collecting arrangement to move at least one of lenses of the focusing/collecting arrangement along an optical axis of the focusing/collecting arrangement to thereby effect variation of a depth of focus, while the exciting radiation is applied to successive sites in the medium during a relative displacement between the system and the medium.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic illustration of a reading/recording system according to one embodiment of the invention;

Figs. 2A to 2C exemplify the operation of the system of Fig. 1;

Figs. 3A and 3B exemplify three examples, respectively, a tight focusing/collecting arrangement according to another embodiment of the present invention suitable for use in a reading/recording system;

Fig. 4 schematically illustrates a reading/recording system according to yet another embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring to **Fig. 1**, there is illustrated an optical system **10** of the present invention designed for reading/recording information in a data storage medium (disk) **16**. As indicated above, the term *"recording"* signifies either one of data writing and erasing processes.

The system **10** includes such main constructional parts as a light source assembly **12**, a detector assembly **18**, and a tight focusing/collecting arrangement **14**. The present invention utilizes simultaneous excitation of desirably distanced from each other sites in the medium (e.g., zero distance, namely the same site), by two exciting light beams of first and second different wavelengths, respectively, and detection of an excited light beam of a third wavelength coming from the excited site. To this end, the light source assembly **12** generates first and second exciting beams $\mathbf{B_1}$ and $\mathbf{B_2}$, which in the present example is implemented by using separate light sources **12A** and **12B**, respectively. It should be understood that these two beams may be both "reading" or both "recording" beams, considering the so-called "two-photon excitation" for each of the reading and recording processes, or may be respectively "reading" and "recording" beams considering the data recording process accompanied by the reading process. It should also be noted, although not specifically shown, that the light source assembly may comprise an additional light source generating radiation serving for erasing the previously recorded data. In this case, the data erasing process would be accompanied by data reading, and thus the two concurrent exciting beams would create "erasing" and "reading" spots. The detector assembly **18** includes a photodetector that may be equipped with wavelength-selective filters and suitable optics (including focusing optics).

The construction of the disk **16** does not form part of the present invention, except to note that it is of either one of ROM (Read Only Memory), WORM (Write Once Read Many), and recordable (rewritable) memory types. More specifically,

the present invention is used with a data storage medium in the form of a monolithic translucent substrate. The monolithic nature of the storage material entails a uniformity of the optical parameters of the disk resulting in a homogeneous index of refraction and absorption coefficient throughout the disk. This allows for designing the focusing device with an aberration corrector of a known range of motion and overall behavior. The disk may for example be designed as described in WO 01/73779 and WO 03070689, both assigned to the assignee of the present application. According to this technique, the substrate medium (active medium, e.g., including diarylalkene derivatives, triene derivatives, polyene derivatives or a mixture thereof) is of the type capable of changing from a first isometric form to a second isomeric form in response to a light beam having energy substantially equal to first threshold energy. The concentration ratio between the first and second isomeric forms in any given volume portion represents a data unit. The active medium may be embedded in a supporting matrix, which may be a polymer, and the active medium is chemically bound thereto. Alternatively the supporting matrix may be a wax or a micelle and the active medium is homogeneously distributed therein. The information is stored as a series of data units. Data reading is based on reading data units from the isomeric states of the active medium in different portions of the active medium, where the two isomeric forms have a substantially different absorption coefficient for absorbing energy of second threshold energy. Reading may also be carried out by measuring the scattering pattern of the two isomeric forms. The disk **16** may be provided with a specific coating, for example for the purposes of protecting it against UV radiation. The disk **16** may for example be protected within a cartridge.

In the monolithic active medium **16**, a data layer is considered as one data set inscribed at a specific depth (within a specified tolerance). Layers with very tight depth tolerance can be considered as having fixed depth. Layers with loose depth tolerances will be termed as layers with variable depth. Data is recorded (written/erased) in a specified layer by changing the state of the substrate within a localized volume element, defined by the focus of the read/write/erase optical

beams. The present invention provides for dynamic focusing of light beams of different wavelengths in a large number of layers with fixed depths, and in a large number of layers of variable depth.

Thus, light source (e.g., laser diode) **12A** is operable to generate a "recording" (e.g., writing) beam of light $\mathbf{B_1}$ of a suitable wavelength range (e.g., visible or UV spectrum, e.g., 660nm) to create data units in the disk, e.g., effect local changes in the medium from the first isometric form to the second isomeric form. Light source **12B** is operable to generate a "reading" beam of light $\mathbf{B_2}$ of a suitable wavelength range (e.g., in the IR spectrum, e.g., 780nm) to affect a radiation response of the medium to the incident radiation $\mathbf{B_2}$. As indicated above, exciting beams $\mathbf{B_1}$ and $\mathbf{B_2}$ to be simultaneously focused may be both reading or both recording beams.

The operation of the light source and detector assemblies enables carrying out in parallel emission of the reading and writing optical beams and the detection of optical response from the disk without any mutual interference between these light signals. As noted above, the light source assembly may also include a light source for producing an "erasing" light spot. Each of the light sources may include more than one laser diode and may generate light beams of different wavelength ranges. It should also be noted that reading of information stored in the disk may be implemented by exciting and measuring the Raman scattering from the disk.

The system **10** also includes light directing arrangement for concurrently directing first and second exciting beams to the focusing/collecting arrangement and directing to the detector a light beam $\mathbf{B_3}$ formed from the emanating excited light (e.g., 500-550nm) collected by the focusing/collecting arrangement. This light directing assembly includes beam splitters **20A** and **20B**, which are preferably wavelength-selective. Beam splitter **20A** transmits the wavelength range of the first exciting beam $\mathbf{B_1}$ and reflects those of the second exciting and excited beams $\mathbf{B_2}$ and $\mathbf{B_3}$, and beam splitter **20B** transmits the wavelength range of second exciting beam $\mathbf{B_2}$ and reflects that of the excited beam $\mathbf{B_3}$, thus spatially separating between illuminating (exciting) radiation and radiation (excited) returned from the disk.

For the purposes of correcting chromatic aberrations of light focusing and collection for light beams of different wavelengths, the system **10** also comprises an exciting beam shaping means located upstream of the focusing/collecting arrangement with respect to the direction of propagation of the excited radiation (the so-called "pre-shaping" means), and an excited beam shaping means located between the focusing/collecting arrangement and the detector assembly (the so-called "post-shaping" means). The main function of the "pre-shaping" means consists of providing the exciting beams arrival at the focusing/collecting arrangement with predetermined degree of the beams divergence or convergence, so as to enable concurrent focusing of the two beams of different wavelengths, with the same focusing/collecting arrangement, onto desirably distanced from each other spots (sites) in the medium, which may for example be the same site (i.e., zero distance). The main function of the "post-shaping" means consists of providing a desired degree of divergence or convergence of the exciting beam when reaching the detector assembly to thereby enabling focusing of this beam onto a light detecting surface. The pre-shaping and post-shaping means are constituted by a lens assembly, which in the present example includes two lenses **22A** and **22B** accommodated in the optical paths of light beams $\mathbf{B_1}$ and $\mathbf{B_2}$ propagating towards the focusing/collecting arrangement **14**. The lens **22B** is also accommodated in the optical path of the collected excited beam and thus serves as the post-shaping means. Possible examples of the system configuration and beams propagation will be described more specifically further below.

The tight focusing/collecting arrangement **14** is constructed and operated to enable the correction of spherical aberrations and the tight focusing of the beams of different wavelengths into the disk with a desired distance between excited spots, and the efficient collection of the excited light of a third different wavelength range from the excited site. The inventors have found that correcting spherical aberrations over a predefined thickness of a specific material for specific wavelengths may be achieved by using only two separate optical assemblies - a first, main lens assembly **14A** (which in the present example of

Fig. 1 is composed of a single lens portion of a specific geometry and material) that performs the majority of the light bending required for the focusing of light, and a second auxiliary lens assembly (corrector) **14B** that mainly compensates for the changing spherical aberration introduced by the changing of the thickness into which the light is being focused. Generally, aberration types that can be corrected are those induced by light traversing through varying depth within the disk material and include for example spherical aberrations and comas.

The lens assemblies **14A** and **14B** are arranged in a spaced-apart relationship along an optical axis **OA** defined by these lens assemblies, with the corrector lens **14B** being accommodated downstream of the main lens **14A**, i.e., closer to the medium **16**. The lenses **14A** and **14B** are appropriately designed to correct for spherical aberrations, while scanning various depths in the medium by two beams of different wavelengths. At least one of the lenses' surfaces is typically aspheric, with no need for complementary shapes of the lens' surfaces. At least one of these lenses **14A** and **14B** is movable along the optical axis. Preferably, the corrector lens **14B** is kept at a certain constant distance from the disk, and the main lens **14A** is movable. In the present example of **Fig. 1**, the system comprises a drive means **26** associated only with the main lens assembly **14A** for moving it along the optical axis, while all the other elements of the system (light sources, detector and corrector) are mounted stationary. The stabilization of corrector lens **14B** at a fixed distance from the disk can be achieved either by using a mechanical actuator (not shown) or by appropriately configuring a holder of the lens **14B** to enable the lens' stabilization by air flow caused by the disk rotation, the so called "flying lens" (Satoshi Shimokawa, et al., "Optical Flying Head System that Featuring Dual-Stage Tracking for Use in High-Density Magneto-Optical Recording", Jpn. J. Applied Phys., Vol. 42, 2003, pp. 873-874).

Thus, in the preferred embodiment of the implementation of system **10**, only the lens **14A** is mounted for movement, while the other elements - corrector **14B**, light sources and detector - are stabilized. This provides for the simplicity

and applicability of the design, as far as mechanics and feedback mechanisms are concerned. Generally, however, at least one of the other elements may be movable as well, namely, as far as degrees of freedom are concerned, one or more optical elements of the system can be moved. Preferably, the corrector **14B** is stabilized at a fixed distance from the disk, either by mechanical actuation or by a flying lens mechanism, and movement only of the main lens is used.

Possible examples of the system configuration and beams' propagation scheme are as follows:

(1) Two exciting beams $\mathbf{B_1}$ and $\mathbf{B_2}$ are both pre-shaped to be collimated (infinite conjugation). In this case, collimating lenses **22A** and **22B** are provided – lens **22A** in the optical path of light generated by light source **12A**, and lens **22B** in the optical path of light generated by light source **12B**. The same lens **22B** serves for post-shaping of the collected excited beam. In this case, the focusing and the correction for spherical and chromatic aberrations are all achieved using lenses **14A** and **14B**, where the main lens **14A** is preferably a "doublet" lens assembly, as will be described further below with reference to Figs. 3A-3B. Parameters of the lenses of the focusing/collecting arrangement in this case are exemplified in Tables 3A and 3B.

(2) Two exciting beams $\mathbf{B_1}$ and $\mathbf{B_2}$ are pre-shaped such that the beams both arrive at the focusing/collecting arrangement as non-collimated (with slight divergence/convergence - the so-called "semi-infinite" conjugation, or with divergence/convergence at a larger degree – "finite" conjugation). It should be understood that, generally, the predetermined degree of the exciting beam divergence/convergence when arriving at the focusing/collecting arrangement can be achieved by appropriately adjusting a distance between the respective light source and the focusing/collecting arrangement. In this case, the pre-shaping is achieved with no specific optical element. Preferably, however, a lens assembly (lenses **22A** and **22B**) is used for this purpose. The lenses **22A** and **22B** are appropriately designed and oriented with respect to the light sources **12A** and **12B** to provide the desired degree of divergence/convergence of the beams propagation,

while arriving at the focusing/collecting arrangement. It should be noted, although not specifically shown, that the same may be achieved by using collimating lenses **22A** and **22B** and additional lenses in the optical paths of collimated beams $\mathbf{B_1}$ and $\mathbf{B_2}$ to further affect these beams to provide the desired degree of non-collimation of these beams when arriving at the focusing/collecting arrangement. It is important to note that in order to achieve tight focusing and collection of different wavelengths through a specific optical path that for itself is not corrected for chromatic aberrations, the incoming beams must approach different divergence or convergence, and the focusing/collection optics must accommodate for the beam divergence/ convergence or focus angle of the beam emerging from the focusing and spherical aberration correction optics. An example of the parameters of the lenses in the case of two diverging/converging beams (two finite conjugations) is given in the following Table 1 (where the surfaces are counted from the laser source to the disk).

Table 1

Surface description	Curvature	Thickness	Glass	Semi-Diameter	Conic
First surface, main lens	1.5251E-02	1.9116E+00	PBH71	3.2146E+00	3.7301E+02
Second surface, main lens	-1.7270E-01			3.3962E+00	-4.8148E+00
First surface, aux lens	-7.1443E+303	1.1460E+00	PBH71	2.3583E+00	-1.7341E+07
Second surface, aux lens	3.8962E+304			1.8738E+00	-5.5793E+38

Aspheric, higher order coefficients:

Surface description	2nd order	4th order	6th order	8th order
First surface, main lens	5.9857E-02	-2.4349E-03	7.3797E-07	-3.8949E-05
Second surface, main lens	1.7276E-02	-3.2527E-04	-3.4591E-04	-3.2331E-07
First surface, aux lens	4.2350E-02	1.0412E-02	-1.4509E-03	1.0142E-04
second surface, aux lens	2.6084E-03	1.9457E-02	-5.3978E-03	1.1652E-04

Surface description	10th order	12th order	14th order	16th order
First surface, main lens	-5.0609E-07	4.0824E-07	-6.9934E-09	-1.3555E-09
Second surface, main lens	2.0342E-06	2.8277E-09	-1.4945E-08	4.8270E-10
First surface, aux lens	2.9057E-05	-7.3741E-07	-6.2739E-07	4.6747E-08
Second surface, aux lens	5.0881E-04	-7.0040E-05	-1.2459E-05	2.1608E-06

(3) Two exciting beams B_1 and B_2 are pre-shaped to arrive at the focusing/collecting arrangement as one collimated and the other slightly diverging/converging (semi-infinite conjugation). This can be achieved by using one collimator for one of the beams, e.g., lens **22B** in the optical path of beam B_2, and appropriate relative accommodation of the other light source with respect to the focusing/collecting arrangement. Alternatively, the collimator is used for one of the beams, while for the other beam, e.g., B_1, an additional lens **22A** is provided being appropriately designed and accommodated with respect to the light source **12A** to provide the desired divergence/convergence of the beam B_1, when the beam arrives at the focusing/collecting arrangement. The parameters of the lenses of the focusing/collecting arrangement are exemplified in Table 2. This table also includes description of the collimating lens in the first optical path, and the "almost collimating" lens in the second path, as well as those of cylindrical lenses **24A** and **24B** (constituting an additional beam shaping means) in the paths of light beams emerging from the light sources (diodes). These lenses **24A** and **24B** are designed to correct for astigmatism effects of the light sources **12A** and **12B**, and affect the beams B_1 and B_2, respectively, to provide substantially circular cross-section thereof. Yet another option is to use collimators **22A** and **22B**, and an additional lens (not shown) accommodated in the optical path of one of the beams B_1 and B_2 to provide the desired degree of the beams' divergence/convergence. In the case of collimated and slightly diverging/converging exciting beams, the optical system is optimized with the pre/post shaping optics for the focusing and collection, and the results is the specified second "collimation" lens.

Table 2

Description	Curvature	Thickness	Glass	Semi-Diameter	Conic
Diode model	0.0000E+00			2.7700E-03	0.0000E+00
First LD astigmatic correction lens, 1st surface	0.0000E+00	5.0000E-01	BK7	3.2473E-03	0.0000E+00
First LD astigmatic correction lens, 2nd surface	0.0000E+00			1.1099E-01	0.0000E+00
First LD "collimating" lens, 1st surface	1.1478E-01	4.0000E+00	BK7	4.1558E+00	-3.2260E+00
First LD "collimating" lens, 2nd surface	-5.6104E-02			4.3303E+00	-4.9254E+00
Main lens 1st surface	7.7291E-02	1.8161E+00	PBH71	3.9066E+00	-2.6716E+00
Main lens 2nd surface	-3.9435E-01			3.9384E+00	-1.3925E+00
Auxiliary lens 1st surface	-1.1396E-01	1.7942E+00	C0550	3.0176E+00	-9.2640E+00
Auxiliary lens 2nd surface	3.4459E-01			2.1210E+00	-9.2528E-01
Second LD astigmatic correction lens, 1st surface	0.0000E+00	5.0000E-01	BK7	2.6651E-03	0.0000E+00
Second LD astigmatic correction lens, 2nd surface	0.0000E+00			9.1761E-02	0.0000E+00
Second LD "collimating" lens, 1st surface	1.1478E-01	4.0000E+00	BK7	3.1635E+00	-2.2673E+04
second LD "collimating" lens, 2nd surface	-5.6104E-02			3.7080E+00	-5.7874E-01

As indicated above, the system of the present invention operates to simultaneously focus two exciting beams of different wavelengths onto desirably distanced from each other sites in the medium, and to collect the excited light of a third different wavelength coming from the interrogated site to form an excited light beam to be detected. The requirement for the distance between the sites is dictated by the operational mode of the system for tracking the data units in the disk, and the formatting of the disk.

For example, a recording laser is to be kept at a fixed focal distance while a reading laser is wobbled around the previous layer so as to ensure tracking using conical scanning. This method of tracking is disclosed in the following patent publications US 20030174594 and WO 03/077240, both assigned to the assignee of the present application. These techniques are aimed at correcting tracking errors while reading/recording in an optical storage medium formed of multiple tracks arranged in different layers. A light spot that is nominally focused on to a track is directed into the optical storage medium. The spot is continually moved in axial and radial directions. A signal having amplitude which varies according to respective offsets from the track in radial and axial directions is received, and used to determine a direction of a respective offset from the track in radial and axial directions, and adjust a location of the reading spot accordingly. A formatting method used in conjunction with said tracking method is disclosed in co-pending U.S. patent application assigned to the assignee of the present application. According to this technique, a formatter for inscription of marks onto a 3D translucent optical medium is provided to enable recording and retrieval of information from the medium. The formatter includes a clamping mechanism to hold the media, an optical unit calibrated to focus at least one diffraction limited spot within the medium at a respective depth therein, a light source optimized for the inscription of marks, and at least one actuator for moving the at least one spot relative to the medium. A data layer is inscribed onto the disc requiring tracking an adjacent layer, thus, recording is achieved by having a first beam-spot reading a first layer, typically by a two photon process and a second beam-spot recording data in a second layer. The requirement emerging from this setup is that the vertical distance between the beam spots will be exactly the required distance between the layers. Another example (also disclosed in the above-indicated co-pending U.S. patent application assigned to the assignee of the present application) utilizes a servomechanism to indicate the location of the read spot relative to tracks formatted in the medium. In this setup, the direction and distance between the read spot and the recording spot need to be

known exactly and tailored to the disc format. The simplest approach would be to have this distance nullified.

Figs. 2A-2C exemplify the operation of the system **10**. Three different steps in the data reading/recording procedure are shown, corresponding to reading/recording of different sites (at different depths) in the medium, respectively. It should be understood that the beam propagation is shown here schematically, and may relate to either one of the above-described cases differing from each other by the exciting beams' arrival at the focusing/collecting arrangement - the plane of the main lens **14A**, namely (1) two exciting beams arriving at the focusing/collecting arrangement are collimated and slightly non-collimated, respectively (infinite and semi-infinite conjugation); (2) both exciting beams arriving at the focusing/collecting arrangement are slightly non-collimated (semi-infinite conjugation); (3) both exciting beams arriving at the focusing/collecting arrangement are collimated (infinite conjugation); and (4) both exciting beams arriving at the focusing/collecting arrangement are non-collimated to a larger degree (finite conjugation).

In this specific example of **Figs. 2A-2C**, which is more relevant to the above cases (1) – (3), than case (4), the main lens **14A** is mounted for movement with respect to the corrector **14B** and to the pre/post shaping means **15** (which may and may not be constituted by a lens assembly, as described above), while the corrector **14B** and the pre/post shaping means **15** are stationary mounted with the corrector being kept at a certain fixed distance from the disk **16**. The focal plane **P** of the entire focusing/collecting arrangement moves inside the disk **16** towards its surface as the main lens **14A** moves away from the corrector **14B**. It should be noted, although not specifically shown, that for the case (4) (finite conjugation of each of the exciting beams), both lens assemblies **14A** and **14B** are preferably moved along the optical axis with respect to the light source and detector assemblies and with respect to the medium. As for case (3), the main lens assembly is preferably a so-called "doublet".

The doublet-based focusing/collecting arrangement of the present

invention is exemplified in **Figs. 3A-3B**. Here, the focusing/collecting arrangement includes a main lens assembly **114A** and a corrector lens **114B**, wherein the main lens assembly is a "doublet" being formed of two portions of different materials and geometries, both being aspheric, and the entire focusing/collecting arrangement serves for correcting both chromatic and spherical aberrations. The different lens' portions $\mathbf{L_1}$ and $\mathbf{L_2}$ are designed so as to process (focus) the beams $\mathbf{B_1}$ and $\mathbf{B_2}$, respectively, and to collect excited light to form beam $\mathbf{B_3}$. In the example of **Fig. 3A**, the two different portions $\mathbf{L_1}$ and $\mathbf{L_2}$ of the main lens assembly **114A** are in the form of two spaced-apart lenses. In the example of **Fig. 3B**, these portions $\mathbf{L_1}$ and $\mathbf{L_2}$ are two lenses attached to each other. The following Table 3 exemplifies the parameters of the doublet-based focusing/collecting arrangement in the example of Fig. 3B:

Table 3

Comment	Curvature	Thickness	Glass	Semi-Diameter	Conic
Doublet first surface	2.7043E-01	2.3679E-01	PBH71	3.2500E+00	-1.0431E+00
Doublet second surface	5.3505E-02	3.5875E+00	C0550	3.0581E+00	3.3296E+01
Doublet third surface	6.4068E-01			3.0014E+00	-7.7739E+00
Auxiliary lens first surface	2.4287E-01	3.3156E+00	PBH71	2.7030E+00	-5.3456E-01
Auxiliary lens second surface	3.1991E-01			1.4370E+00	-9.3719E-01

Aspheric, higher order coefficients:

Comment	2nd order	4th order	6th order	8th order
Doublet first surface	1.0401E-01	-2.7209E-03	5.3114E-05	4.8599E-05
Doublet second surface	2.9812E-01	-2.9169E-03	4.0955E-04	2.6000E-05
Doublet third surface	4.3648E-02	-1.2087E-02	-1.2758E-04	2.8437E-05
Auxiliary lens first surface	-8.6208E-02	-6.2827E-04	8.6621E-05	-3.6727E-05
Auxiliary lens second surface	-1.1991E-01	-4.2867E-04	5.2429E-03	-7.7184E-03

Comment	10th order	12th order	14th order	16th order
Doublet first surface	-6.5926E-06	-1.7765E-07	5.3165E-08	-2.6789E-09
Doublet second surface	5.4191E-06	-1.5094E-06	-3.6657E-07	3.7156E-08
Doublet third surface	-1.1353E-06	-1.3887E-07	3.0890E-08	-1.7986E-09
Auxiliary lens first surface	8.4868E-06	-1.1913E-06	9.3002E-08	-3.0991E-09
Auxiliary lens second surface	6.5593E-03	-3.2709E-03	8.9057E-04	-1.0237E-04

Referring to **Fig. 4**, there is schematically illustrated an optical system **200**, according to yet another embodiment of the invention, for reading/recording data in a disk **16**. To facilitate understanding, the same reference numbers are used to identify those components that are common in the examples of Figs. 1 and 4. The system **200** comprises a light source assembly **12**, which in the present example includes two light sources **12A** and **12B**; a detector assembly **18**; wavelength-selective beam splitters **20A** and **20B**; a lens assembly including lenses **22A** and **22B** (constituting pre-shaping and post-shaping means), and preferably also lenses **24A** and **24B** for affecting the cross-section of the emitted exciting beams $\mathbf{B_1}$ and $\mathbf{B_2}$; a focusing/collecting arrangement **214**; and a drive means **26**.

In the present example, the focusing/collecting arrangement comprises an objective lens arrangement **214A** and an aberration correction assembly **214B** that are arranged in a spaced-apart relationship within the optical path **OA** of the focusing/collecting arrangement, wherein the objective lens assembly **214A** is located closer to the disk **16** and the aberration correction assembly **214B** is a multiple-lens assembly. In the present example, the corrector **214B** includes three optical elements (lenses) $\mathbf{L_1}$, $\mathbf{L_2}$ and $\mathbf{L_3}$. The correction of spherical aberration is attained by varying the position of the corrector relative to the objective lens arrangement and relative to the disk, as the depth of focus within the disk material is altered. This requires relative displacement of at least an intermediate lens $\mathbf{L_2}$ of the corrector along the optical path **OA**, and possibly also a relative displacement between the objective lens **214A** and the disk. In the present

example, the drive means **26** is associated with both the corrector lens $\mathbf{L_2}$ and the objective lens. The drive means **26** may be of the kind providing a mechanical displacement of the corrector lens $\mathbf{L_2}$ or a motor driving the corrector for movement along the optical axis **OA** in conjunction with the movement of the focusing lens assembly **214A,** in accordance with the predicted behavior of the spherical aberration for a given depth of focus.

In all the examples of the invention, the movement of the optical element(s) may be controlled by using a feedback mechanism from the photodetector **18** sensitive to the tightness of the focus of reading/recording beams, or may be controlled using a feedback from a mechanical device, and optionally using depth information that was inscribed onto the disk in a previous stage.

The optical system of the present invention is designed to operate with a broad range of depths, e.g., 0-3 mm, with high numerical aperture, e.g., NA>0.5, taking into account the nature of the storage material, the range of motion necessary, and the wavelengths of light in use, while continuing the compensation for the spherical aberration over the whole range of motion. Either one of semi-infinite, infinite and finite conjugate implementations can be used.

Those skilled in the art will readily appreciate that modifications and changes can be applied to the embodiments of the invention as hereinbefore exemplified without departing from its scope defined in and by the appended claims.